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User's Manual for CHANLPRO, PC Program for Channel Protection Design

by Stephen T. Maynord, Martin T. Hebler, Sheila F. Knight

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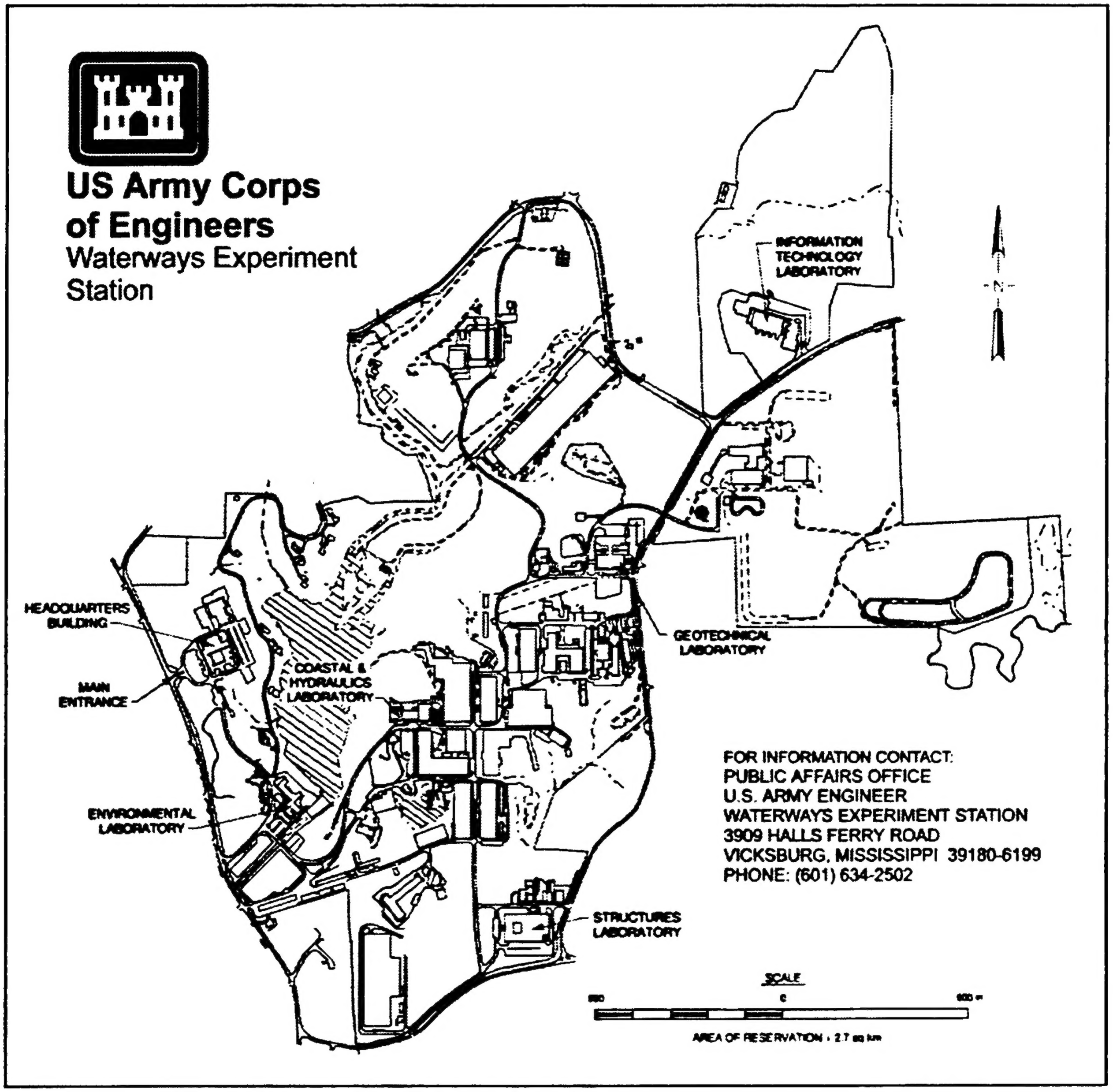

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Preface

The work described in this report was sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Flood Control Structures Research Program under Civil Works Investigation Work Unit 32686, "Riprap Toe and End Section Design." HQUSACE Program Monitor was Mr. Tom Munsey.

The work was performed by personnel of the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Waterways Experiment Station (WES), during 1995-1998. The study was accomplished under the direction of Dr. James R. Houston, Director, CHL, and Mr. Charles C. Calhoun, Jr., Assistant Director, CHL. The study was conducted by Dr. S. T. Maynord and Ms. Sheila Knight of the Navigation Branch, Navigation and Harbors Division, CHL, and Mr. Martin Hebler, Hydraulic Analysis Group, Estuaries and Hydrosciences Division, CHL. This report was written by Dr. Maynord, Mr. Hebler, who also did the FORTRAN coding, and Ms. Knight, who also did the Visual Basics coding.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Robin R. Cababa, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
degree (angle)	0.01745329	radians
feet	0.3048	meters
inches	25.4	millimeters
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
tons (long mass)	1016.647	kilograms

1 Introduction

General

This document provides a user's manual for Windows program "CHANLPRO," which replaces RIPRAP15 and addresses three areas pertinent to the design of channel protection. First, the program contains the U.S. Army Corps of Engineers (USACE) riprap design guidance for placement in the dry for channels subjected to velocity forces in low turbulent flow based on guidance found in USACE (1994). For underwater placement, riprap thickness from CHANLPRO should be increased by 50 percent. Second, the program provides guidance for the design of gabion mattresses for the same flow conditions as the riprap design guidance. The gabion sizing guidance is based on Maynord (1995). Third, the program provides guidance for estimating scour depth in erodible channels based on guidance given in Maynord (1996a). The program does not address high turbulent environments found near hydraulic structures, which have turbulence generated by features such as hydraulic jumps. Riprap below hydraulic structures should be designed using guidance in USACE (1990). Data used to develop the methods used herein for riprap and gabion mattresses were limited to channel slopes less than or equal to 2 percent. Guidance for channel slopes greater than 2 percent and for riprap subject to impinged flow can also be found in USACE (1994). CHANLPRO uses English foot-pounds per second units because the stone industry in the United States primarily operates in these units.

CHANLPRO differs from its predecessor, RIPRAP15, as follows:

a. CHANLPRO incorporates Plate B-33 from USACE (1994) (see Figures 1 and 2) for velocity estimation in natural and trapezoidal channels when using the average channel velocity option. Figure 1 (Plate B-33) for natural channels is the same as in RIPRAP15. Figure 2 (Plate B-33) is applicable to channels having equal bottom and side-slope roughness. CHANLPRO limits V_{ss}/V_{avg} to greater than or equal to 1.0 on Plate B-33 when using the average channel velocity option (see Chapter 2, "Input"). V_{ss} is the local depth-averaged velocity at 20 percent upslope from the toe. V_{avg} is the average channel velocity in the main channel, excluding

overbank areas. When using the average channel velocity option, CHANLPRO defines values of V_{ss}/V_{avg} less than 1.0 for channels that are straight for a sufficient distance downstream of bends or other channel features that create a flow imbalance (see Chapter 2 for details). The program uses the curve from Figure 3 for equal bottom and side-slope roughness ($n_{bed}/n_{bank} = 1.0$), which is taken from Maynord (1996b).

b. CHANLPRO incorporates calculation of bottom protection size in trapezoidal channels.

c. CHANLPRO removes unit weight limitation of 5-lb[1] increments.

d. CHANLPRO allows alternate user-specified riprap gradations in areas where the riprap gradations in ETL 1110-2-120 (USACE 1971) are not used. ETL gradations are also given in USACE (1994).

e. CHANLPRO incorporates riprap thickness effects (Figure 4) for alternate riprap gradations having D_{85}/D_{15} from 1.7 to 5.2. RIPRAP15 only allowed thickness effects for ETL gradations. For riprap gradation uniformity coefficient $D_{85}/D_{15} > 5.2$, CHANLPRO uses the value of C_t for $D_{85}/D_{15} = 5.2$. Minimum riprap thickness is N=1, which is $1D_{100}$(max). This method is limited to N = 1, to 2 because riprap is rarely placed thicker than $2D_{100}$.

f. CHANLPRO uses a changed riprap output format. Multiple stable gradations are output at required thickness.

g. CHANLPRO has added the option to determine gabion thickness based on Maynord (1995), which uses the same equations as the riprap design option.

h. CHANLPRO has added the option of determining the scour depth in a bend, based on Maynord (1996a).

i. CHANLPRO has eliminated the rerun option and replaced it with a point-and-click Visual Basics interface.

j. CHANLPRO is also designed to accept input files and write output to a file.

As this program has evolved to its present form, so has the recognition that the most uncertain aspect of riprap design is the determination of the imposed force. In this method, the imposed force is determined using the depth-averaged velocity at the point of interest. For this reason, many of the changes and much of the

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vi.

required input are directed at helping the designer determine the local depth-averaged velocity.

Basic Equations

Riprap design equations

From USACE (1994), the equation for stone size is

$$D_{30}=S_f C_S C_v C_T d[(\frac{\gamma_w}{\gamma_s-\gamma_w})^{1/2}\frac{VL}{\sqrt{K_1 g d}}]^{2.5} \qquad (1)$$

where

D_{30} = characteristic riprap size of which 30 percent is finer by weight. D_{30}(min) of available riprap gradation must be greater than or equal to D_{30}.

S_f = safety factor, minimum = 1.1

C_s = stability coefficient for incipient failure, thickness = $1D_{100}$(max) or $1.5D_{50}$(max), whichever is greater, valid for gradation uniformity coefficient D_{85}/D_{15} = 1.7 to 5.2. C_s is not an input in CHANLPRO and is fixed at 0.30 for angular rock.
= 0.30 for angular rock
= 0.375 for rounded rock

C_V = velocity distribution coefficient
= 1.0 for straight channels
= 1.0 for inside of bends
= 1.283-.2log(R/W) for outside of bends for R/W < 26
= 1 for R/W > 26 (see Figure 4)
= 1.25 downstream of concrete channels
= 1.25 at end of dikes

R = centerline radius of bend, main channel flow only

W = water surface width at upstream end of bend, main channel flow only

C_T = blanket thickness coefficient (see Figure 4)

d = local depth, use depth at 20 percent upslope from toe for side slopes

γ_s = unit stone weight

γ_w = unit weight of water

VL = local depth-averaged velocity, which is the characteristic velocity used in this procedure. For side-slope riprap, the depth-averaged velocity at 20 percent upslope from the toe V_{ss} is used for VL. To emphasize this point, V_{ss} is only used for side-slope riprap and is always the depth-averaged velocity 20 percent upslope from the toe.

K_1 = side-slope correction factor, see Figure 5.

The power of 2.5 in Equation 1 was based on laboratory riprap stability data from straight, tilting flumes. The extreme values of the power in Equation 1 are from 2 to 3. A power of 2 results in the Isbash equation (no dependence on depth) and is generally used when there is little boundary layer development. A power of 3 results from application of existing shear stress and the Manning-Strictler equations and represents the condition of completely developed boundary layer and a relative roughness (roughness size/depth) that is low enough to yield a constant Shields coefficient. Most bank and channel riprap protection problems fall somewhere between these two extremes. This led to the adoption of the 2.5 power for all bank and channel riprap protection problems, not just the straight, tilting flumes from which it was derived.

The stability coefficient C_s defines the point at which the rock blanket begins to fail. This means minor rock movement will occur, but not enough to fail the blanket. This movement is generally restricted to the smaller particles and/or particles that are in unstable positions typical of machine-placed riprap.

Gabion design equations

The basic equation used in the gabion design portion of CHANLPRO is identical to the riprap design equation except that the thickness coefficient C_t is not applicable, C_s is equal to 0.1 for rock in a gabion basket, and the characteristic rock size is D_{50}. C_s equal to 0.1 ensures that the rock will not move around in the basket, which would result in basket deformation and possibly additional wear on the basket wire. Velocity estimation techniques are identical in the riprap and gabion design methods. CHANLPRO takes the computed D_{50} and rounds it up to the nearest 1/2 in. and then multiplies the rounded D_{50} by 2 to determine the thickness of the gabion. Rock gradations used in the gabion mattresses should have a maximum size/minimum size of 1.5 to 2.0. Gradation uniformity for gabions is generally expressed as maximum to minimum as opposed to D_{85}/D_{15} used in riprap design.

Scour depth estimation equation

Details of the development of this scour depth method are provided in Maynord (1996a). The basic equation used in the scour depth estimation portion of CHANLPRO is

$$\frac{D_{mxb}}{D_{mnc}} = SF[1.8 - 0.051\ R/W + 0.0084\ W/D_{mnc}] \qquad (2)$$

where

D_{mxb} = maximum water depth in bend

D_{mnc} = average depth in the crossing upstream of the bend

SF = safety factor defined in Table 1

Table 1
Safety Factor Versus Percent of Significantly Unconservative Data

Safety Factor	Percent of Data Having Computed D_{mxb}/Observed D_{mxb} Less Than 0.95
1.0	25
1.03	20
1.08	10
1.14	5
1.19	2

[1] Significantly unconservative data are defined in Maynord (1996a) as data having the (computed maximum water depth in the bend D_{mxb})/(observed maximum water depth in the bend D_{mxb}) less than 0.95. Stated otherwise, the computed D_{mxb} must be more than 5 percent less than the observed D_{mxb} before a data point is defined as unconservative. This approach attempts to recognize the fact that scour is hard to measure and that any computation within 5 percent of the observed is adequate.

A minimum safety factor for scour depth estimation of 1.14 is recommended and Equation 2 should be limited to R/W from 1.5 to 10 and aspect ratio W/D_{mnc} from 20 to 125. For bends having R/W less than 1.5, CHANLPRO uses scour depth for R/W = 1.5. For channels having aspect ratios less than 20, CHANLPRO uses scour depth for W/D_{mnc} = 20.

Design Conditions

Channel protection should be designed for the combination of velocity and depth that gives the largest protection size. This combination is not always the design discharge. In many cases, bank-full discharge produces the combination

of velocity and depth that results in the largest protection size. Protection size in bendways is normally based on the maximum V_{ss} found along the bend. Bendways having stable upstream conditions could be designed with a variable protection size along the bend. This is generally not done because specification of multiple protection sizes has been found in some cases to increase construction costs.

Velocity Estimation

The primary reason for adopting a design procedure based on depth-averaged velocity is because several techniques exist for estimating velocity. Velocity is also easy to visualize and measure compared to shear stress. Any channel protection design problem has two parts. First, the imposed force is estimated. Second, the imposed force is used to determine protection size. The most difficult and most uncertain part of channel protection design lies in estimating the imposed force, whether it be local depth-averaged velocity or shear stress. When protection is designed for a channel bottom, local depth-averaged velocity is a straightforward concept even if it may be difficult to determine. When side-slope riprap is designed, local depth-averaged velocity varies greatly from toe of slope to waterline and near-bank velocity is meaningless unless the position is specified. The USACE (1994) method uses depth-averaged velocity at a point 20 percent upslope from the toe V_{ss} for side-slope riprap design. The 20-percent point was selected because straight channel side-slope stability tests resulted in the same stability coefficient C_s as straight channel bottom stability tests with this position on the side slope and the appropriate adjustment for side-slope angle. This point is consistent with the location of maximum side-slope shear stress from straight channel studies.

Various tools exist to estimate depth-averaged velocity for use in riprap design, including the following, with some of their limitations:

a. Numerical models: two-dimensional (2-D) depth-averaged numerical models have been shown to provide computed velocity lower than observed velocity along the outer bank in prismatic bends. Bernard (1993) has developed a correction method for 2-D depth-averaged models, and a version is available that can be used with personal computers. This model has compared well with data from trapezoidal and natural channels.

b. Physical models: rarely available for bank protection projects due to cost. If available, near-bank velocity distributions should be measured to obtain V_{ss}.

c. Empirical methods: As in the procedure used herein, empirical methods must be applied only to cases similar to the data from which they were derived.

d. Analytical methods: methods based on conveyance such as ALPHA method given in USACE (1994) should be limited to straight channels because secondary currents cause ALPHA to be unconservative.

e. Prototype data: normally require extrapolation to design conditions, but are usually not available.

Characteristic Particle Size for Riprap Gradations

One of the most controversial changes from the old riprap design guidance to the new has been the adoption of a characteristic particle size of D_{30}. Stability tests conducted at a thickness of $1D_{100}$, which is the most commonly used thickness for bank protection, showed that gradations ranging from uniform to highly nonuniform exhibited the same stability if they had the same D_{30}. Maynord (1988) documents other investigators who found a characteristic size less than the commonly used D_{50}. It is likely that if the tests had been conducted at another thickness such as $1.5D_{100}$, the resulting characteristic size would have been different and probably larger. The use of D_{30} instead of D_{50} requires that the designer determine which of the available gradations has a D_{30}(min) greater than or equal to the computed D_{30} rather than to D_{50}. One of the results of this finding is that uniform gradations use the least volume of rock to achieve the same stability because the thickness is equal to the maximum stone size. One of the troubling aspects of these results is that an investigator of riprap subjected to channel flow has not yet been found who has been able to confirm the commonly held notion that a range of sizes gives increased stability due to better interlock. The use of a single particle size to characterize a gradation, whether D_{30}(min) or D_{50}(min), does not reflect all the characteristics of that gradation. The following equation can be used to determine if D_{30}(min) is representative or if D_r(min) should be used as the characteristic particle size:

$$D_r(\min) = \sqrt[3]{D_{85}(\min) D_{15}(\min)^2} \qquad (3)$$

If D_r(min) is significantly different from D_{30}(min), use D_r(min).

One factor that should be considered is the impact of gradation on filter requirements. If a granular filter is used, the lower sizes of the riprap gradation must properly interface with the upper sizes of the filter. Consequently it is difficult to use a large uniform riprap and economically interface it with a granular filter. With geotextiles, this is not a problem, but a bedding layer is sometimes used on top of the geotextile to prevent damage while placing the riprap.

Riprap Packing

Some Corps Districts tamp or pack riprap after placement with a heavy plate or a wide-tracked dozer to achieve increased stability. This action tends to produce a more compact mass of riprap having greater interlock. Limited tests (Maynord 1992) showed that tamping allowed a size reduction of 10 percent compared to normal placement techniques.

Effects of Filter Type

The stability tests used in the determination of $C_s = 0.3$ were conducted on a filter fabric. Limited tests (Maynord 1992) showed that placement of riprap on a granular filter allowed a size reduction of 10 percent compared to placement on a filter fabric. This reduction is considered applicable only to the minimum blanket thickness equal to the maximum stone size ($1D_{100}$). Greater rock thickness would tend to minimize the impact of the filter.

2 Input

General

CHANLPRO uses various windows to input parameters. It contains a help feature that is invoked by clicking the "?" beside any parameter. The program starts with an introductory visual scene of a riprap protection project and then requires that the user select riprap design, gabion design, or scour depth estimation. Program input is as follows:

Input for Riprap Design

a. After selecting "riprap design," the program requests **Input from file or keyboard.** Program can be run by keyboard entry or from input file. If input is from a file, an input filename will be requested. Example input files are shown in Figure 6. Note that the format changes with the various options in the program. It is generally easiest to use the program to generate the input file and then use a text editor to modify input for other applications. The two-letter designator used in the input files and defined in Figure 7 is a required part of the input file and assists the user in knowing which parameter is used on each line of the input file.

b. **Save input data to a file or not.** If "save input data to a file" is chosen, the program will ask for an input file name and will store keyboard entries for later use as an input file.

c. **Identification line.** Used to identify input files. Not requested if not saving the input file. For no identification line, choose OK and leave the input box blank.

d. **Straight reach or bend.** Note that a straight reach immediately downstream of a bend should have rock size the same as the bend. USACE (1994) provides guidance on decay of velocity downstream of a bend.

e. **How is local velocity determined?** Select either "User inputs local depth averaged velocity" or "User inputs average channel velocity and program computes local depth averaged velocity." This is the main source of confusion in using this program. The two options refer to the method in which local depth-averaged velocity will be determined by the program. If local depth-averaged velocity is input by the user, it means that the user has already determined local depth-averaged velocity VL (which could be V_{ss} if side-slope riprap is being designed) and will input the value directly. Methods for determining VL include numerical models, physical models, prototype measurements, etc.

   If "user input average channel velocity ...." is chosen, the program is selecting local depth-averaged velocity from Plate B-33 (Figures 1 and 2). The user will be required to input radius, width, average channel velocity, and other parameters on Plate B-33, depending on channel type. For Plate B-33 to be valid, the design problem should be a single channel and all channel descriptors such as average velocity, width, radius, etc. should be based on flow in the main channel only. Plate B-33 can be used for problems with shallow overbank flows but the descriptors must be based on only the flow in the main channel.

f. **Natural or trapezoidal channel.** A natural channel is one that is free to scour the bed along the outer bank and build a point bar on the inner bank. A natural channel means that side-slope protection is being designed and that Plate B-33, Sheet 1 of 2 (see Figure 1) will be used to determine local depth-averaged velocity on the side slope at 20 percent upslope from the toe. For $R/W < 2$, the program uses V_{ss}/V_{avg} for $R/W = 2$. A trapezoidal channel is one in which the trapezoidal shape is expected to remain and often involves protection of both the invert and side slopes.

g. **Is straight reach more than five channel widths downstream of anything causing a flow imbalance?** (Trapezoidal channel only). For trapezoidal channel, side slope, straight reach, and more than five channel widths downstream of a flow imbalance, the program uses Figure 3 with $n_{bed}/n_{bank} = 1$ to compute V_{ss}/V_{avg} which will often be less than 1.0. If trapezoidal channel, side slope, straight reach, and not more than five channel widths downstream of a flow imbalance, then the program uses a minimum $V_{ss}/V_{avg} = 1.0$.

h. **Invert or side slope.** (Trapezoidal channel only). For invert (channel bottom) protection in a trapezoidal channel, the local depth-averaged velocity is set equal to the greater of the following:

   (1) 1.15 times the average channel velocity.

   (2) V_{ss} from Plate B-33, Sheet 2 of 2 (see Figure 2).

If side-slope protection is being designed in a trapezoidal channel, the program uses Plate B-33, Sheet 2 of 2 (see Figure 2) to determine the depth-averaged velocity 20 percent upslope from the toe. The following rules apply to Plate B-33:

(1) For R/W<2, use V_{ss}/V_{avg} for R/W=2. For R/W>50, use V_{ss}/V_{avg}= 1.0.

(2) For bend angle=0, V_{ss}/V_{avg} = 1.0. For bend angle>120, use V_{ss}/V_{avg} for bend angle = 120.

(3) For (bottom width)/(max flow depth) < 3.3, use V_{ss}/V_{avg} for (bottom width)/(max flow depth) = 3.3. For (bottom width)/(max flow depth) > 10, use V_{ss}/V_{avg} for (bottom width)/(max flow depth) = 10.

i. **Bend angle, bottom width, maximum flow depth.** (Trapezoidal channel only). These parameters are only used to estimate V_{ss} in curved trapezoidal channels. Bend angle range is 0 to 120 deg. The ratio bottom width/maximum flow depth is limited to 3.3 to 10. Values outside this range can be used, but V_{ss} will be based on the value at bottom width/maximum flow depth of 3.3 or 10.0.

j. **Bend radius, ft.** Enter the bend radius for flow in the main channel only at the upstream end of the bend.

k. **Water surface width, ft.** Enter water surface width for flow in the main channel only at the upstream end of the bend.

l. **Unit weight of stone, lb/ft^3.** Enter value from 135 to 185. Unit weight of stone increments of 5 lb/ft^3 are no longer required.

m. **ETL or alternate gradation.** The program allows the use of the ETL gradations found in USACE (1971) or user-specified alternate gradations. The ETL gradations for dry placement in low turbulent flow are reproduced in Table 3-1 of USACE (1994). The relation between weight and equivalent diameter in the ETL gradations is based on a sphere. D_{100}(max) for ETL gradations are in 3-in. increments from 9 to 36 in. and in 6-in. increments from 36 to 54 in. Alternate gradations must be saved in a file "ALT.GRD," which is shown in Figure 8 and must be in the same directory as CHANLPRO. For each alternate gradation, enter a 10-character name with no blanks, D_{30}(min) in ft, D_{100}(max) in inches, and D_{85}/D_{15}. All alternate gradations must have the same unit stone weight.

n. **Local flow depth, ft.** The local flow depth is the depth at the location at which the riprap is being designed. For bottom protection in trapezoidal channels, local flow depth = maximum flow depth. For side slopes in natural channels, local flow depth is the depth 20 percent upslope from

the toe. For side slopes in trapezoidal channels, local flow depth is the depth 20 percent upslope from the toe and local flow depth = 0.8 * maximum flow depth.

o. **Cotangent of side slope.** Must be greater than or equal to 1.5. The least volume of riprap/unit length of eroding bank generally at cotangent of side slope = 1.75. For bottom riprap, specify cotangent of side slope = 4 or greater to invoke no side-slope influence. Figure 5 provides guidance for side-slope effects.

p. **Safety factor.** The recommended minimum safety factor is 1.1. Increase the safety factor for uncertainty in input parameters unless conservative values are used. Consider consequence of failure in selection. The safety factor can be used to incorporate other riprap design corrections that are not programmed, such as the use of rounded rock or riprap downstream of a concrete channel. In both cases, a 25-percent increase in rock diameter is recommended in USACE (1994). If a safety factor of 1.1 is desired for use with rounded rock, enter safety factor = 1.1(1.25) = 1.375.

Input for Gabion Design

The input for gabion design is identical to riprap except that no input is required for ETL versus alternate gradations.

Input for Scour Depth Estimation

All input to the scour estimation routine are lengths whether they are depth, width, or radius. Consequently, input in feet will be output in feet and input in meters will be output in meters.

a. **Safety factor**. The safety factor is based on Table 1 and defines the percentage of data points that are significantly unconservative, which is defined as computed D_{mxb}/observed D_{mxb} less than 0.95. A minimum safety factor of 1.14, which results in 5 percent of the data being significantly unconservative, is recommended.

b. **Centerline radius of bend.** As in the riprap design routine, the required radius is for flow in the main channel.

c. **Water-surface width.** As in the riprap design routine, the required width is for flow in the main channel at the upstream end of the bend.

d. **Average depth in crossing upstream of bend.** Also for flow in the main channel, D_{mnc} should be calculated from (main channel area) / (main channel water surface width).

3 Output

Output for Riprap Design

Riprap output in CHANLPRO consists of (a) return of the input parameters plus some of the derived parameters such as K_1, C_v, and the local depth-averaged velocity, and (b) selection of a range of stable gradations.

Example outputs are shown in Figures 9 through 12 for various program options and correspond to the input files in Figure 6.

The table titled "Selected Stable Gradations" for both ETL and alternate gradations contains the following information:

a. **Name.** ETL gradations are named by the numbers 1-13 for D_{100}(max) from 9 to 54 in. Alternate gradations are named by the 10 characters in the file "ALT.GRD."

b. **Computed D_{30}.** This is the value from Equation 1. No value is shown for unstable gradations.

c. **D_{30}(min).** This value comes from the lower, or minimum, curve that characterizes a given gradation. The "30" represents 30 percent finer by weight. For ETL gradations, the first value shown is the largest gradation that is not stable at any thickness. All other gradations that follow can be placed to a thickness that will be stable.

d. **D_{100}(max).** Maximum stone size in the available gradations. Use to establish the thickness which is always >= 1.0 D_{100}(max).

e. **D_{85}/D_{15}.** Uniformity of available gradations. Equal to 1.7 for ETL gradations. Determined by taking the average D_{85}/D_{15} of the upper and lower limit curves.

f. **N = Thickness/D_{100}(max).** CHANLPRO determines the required N between 1 and 2 for each stable gradation.

g. **C_t.** Used in Equation 1 and defined by N and D_{85}/D_{15} from Figure 4.

h. **Thickness.** Thickness = N*D_{100}(max). For example, in Figure 9, CHANLPRO computes that ETL gradation "2" is stable for N = 1.35 or 1.35*D_{100}(max) = 16.2". ETL gradation "3" is stable if placed to N =1 or 1.0*D_{100}(max) = 15". Thus, a smaller gradation placed to a greater thickness provides adequate (but not equal!) stability. ETL gradation "3" has a larger safety factor.

In Figure 10 for alternate gradations, adequate stability is provided by a 39.6-in. thickness of Graded No. 3 (different from ETL gradation 3), 30.1-in. thickness of Graded No. 4, or 36 in. of Graded No. 5 (36 in. is the minimum thickness for Graded No. 5 because the minimum thickness for any gradation is 1.0*D_{100}(max)). Although thickness in CHANLPRO is shown to the nearest 0.1 in., thickness should be specified in contract drawings to the nearest inch plus a reasonable tolerance which depends on the absolute size of the riprap and placement considerations.

Output for the ETL gradations will include the largest unstable gradation up to the size for which the thickness is 1.0D_{100}(max), which is N=1. RIPRAP15 selected only the gradation having N=1. Output for alternate gradations will be for all gradations that are stable. When evaluating the stable gradations, one should not assume that they all have equal stability. For example, in Figure 9 the gradation having a D_{100}(max) = 9 in. is not stable at any thickness from N = 1 to 2 (Figure 4). The gradation having a D_{100}(max) = 12 in. is stable if placed to a thickness of 16.2 in. The gradation having a D_{100}(max) = 15 in. is stable if placed to a thickness of 15 in. The 16.2-in.-thick and 15-in.- thick gradations do not have equal stability but they both satisfy the requirements of this problem. The actual safety factor can be determined as 1.1(D_{30}(min)/Computed D_{30}). Therefore, the D_{100}(max) = 12 in. placed 16.2 in. thick has a safety factor of 1.1(0.48/0.48)=1.1. The D_{100}(max) = 15 in. placed 15 in. thick has a safety factor of 1.1(0.61/0.52)=1.29. In this case, the 15 in. D_{100}(max) riprap would likely be the best choice unless the smaller gradation was readily available and cheaper.

For ETL gradations only, the selected stable gradations are followed by the upper and lower limits of stone weight at the 100, 50, and 15 percent lighter by weight and the D_{30}(min) and D_{90}(min) diameters (based on equivalent spherical diameters). Equivalent spherical diameters are then given for max and min values of D_{100}, D_{50}, and D_{15}.

Output for Gabion Design

Output for the gabion routine is the minimum average filling rock diameter and the minimum mattress thickness. The computed minimum mattress thickness is often not one of the standard mattress thicknesses which are generally 6, 9, 12, and 18 in. In these cases, the designer would select the next

larger standard mattress thickness and use fill rock of the size computed by the program.

Output for Scour Depth Estimation

The output for the scour depth estimation is the maximum **water** depth in the bend, not the maximum scour depth. To determine the maximum scour depth, subtract the existing depth in the bend from the maximum depth in the bend given by the program. As stated previously, whatever units are used for width, radius, and mean crossing depth will be the units output for maximum water depth in the bend.

4 Applications

Many bank protection problems have a small portion of the channel perimeter covered with riprap and the average channel velocity is not significantly affected by the added resistance of the riprap. In these cases, determination of required riprap or gabion thickness is a direct, one-time-through solution.

For those few channels having protection on both the invert and the side slopes, the flow depth and average channel velocity will vary with protection size because resistance varies and an iterative solution is required. A trial protection is assumed, resistance values are determined for the trial protection, and flow depth and velocity are computed with a water surface profile method. Riprap or gabion size is then determined for the computed depth and velocity. If the computed protection size is greater than the trial protection, a larger trial protection is assumed and the process is repeated until the trial protection is greater than or equal to the computed protection. For this type of iterative solution, the output of multiple stable gradations from CHANLPRO should be used with caution. The only valid stable gradation is the gradation for which the resistance values were used to compute the depth and velocity input into CHANLPRO.

In most cases, a channel protection problem requires consideration of how to apply CHANLPRO to fit the given circumstances. Consider the project where riprap was placed downstream of a concrete channel having subcritical flow and failure of the riprap occurred immediately downstream of the end of the concrete. The lower end of the concrete channel had a bend followed by a flare of about 1:4 which was too fast an expansion for the flow to follow and separation occurred. The side slopes of the concrete and riprap channels were 1V:2.5H, but the riprap failure occurred on the channel bottom. An observer of a high flow reported that the flow was against the right side of the channel and that an eddy formed resulting in flow going upstream along the left one-third of the channel width at the concrete/riprap interface. The average channel velocity across the entire width at the concrete/riprap interface was 8 ft/sec. It is possible that the existing riprap failed because this average velocity was used to design the riprap. The depth at the design flow was about 15 ft and the available stone has a unit weight of 165 lb/ft^3. What ETL gradation would be stable for this problem? The first and biggest problem is to determine the design velocity to use in sizing the

protection. The option "user inputs average channel velocity..." would be of no use in this problem because the curves in Figures 1 and 2 are not applicable. The option "User inputs local depth averaged velocity" will have to be used but the velocity must be determined external to the CHANLPRO program. Physical or numerical models are not justified and prototype data are not available. This project requires the user to make an educated guess as to the depth-averaged velocity to use in design. If the left third is not passing flow in a downstream direction, the effective area must be about two-thirds of the total area, which means that the average velocity through the right two-thirds must be 1.5(8) = 12 ft/sec. If the average is 12, the maximum must be greater. Estimated maximum local depth-averaged velocity is 15 percent greater than average channel velocity (typical of the increase found in straight channels) and use of a depth-averaged velocity for design = 1.15(12) = 13.8 ft/sec. Using CHANLPRO with the above parameters, a cotangent of side slope of 4 to eliminate side-slope effects, and a safety factor of 1.1(1.25)=1.375 to account for the smooth to rough boundary (see USACE (1994)) results in an ETL gradation of $D_{100}(max)$ = 27" placed to a thickness of 27" or a gabion mattress thickness of 9". This larger riprap would be placed a distance downstream in the riprap channel far enough for the vertical profile and the lateral velocity distribution to stabilize, about 3-5 channel widths or 5-10 channel depths, whichever is greater.

5 Summary

CHANLPRO is a PC program for designing riprap revetment and gabion mattresses, and for defining scour depth in alluvial channels. The riprap design portion of the program is a modification of PC program RIPRAP15.

References

Bernard, R. S. (1993). "STREMR: Numerical model for depth-averaged incompressible flow," Technical Report REMR-HY-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

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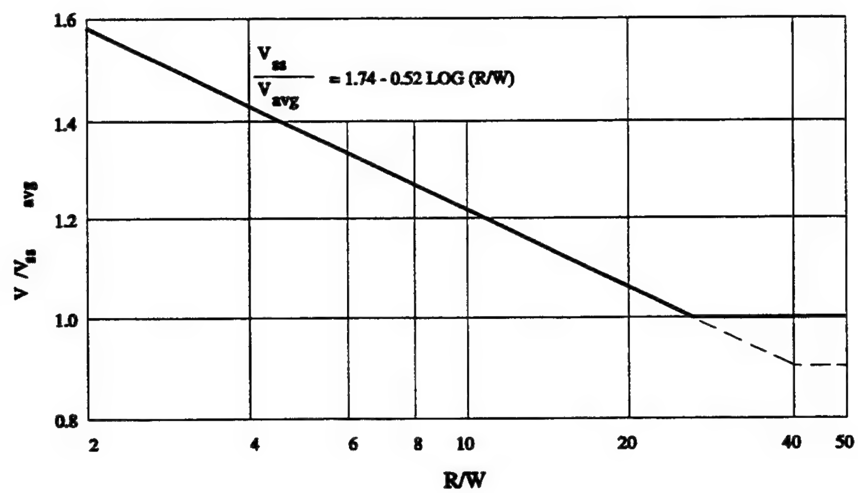


NOTE: V_{ss} IS DEPTH-AVERAGED VELOCITY AT 20 PERCENT OF SLOPE LENGTH UP FROM TOE

RIPRAP DESIGN VELOCITIES
NATURAL CHANNEL

Figure 1. Velocity estimation for natural channels

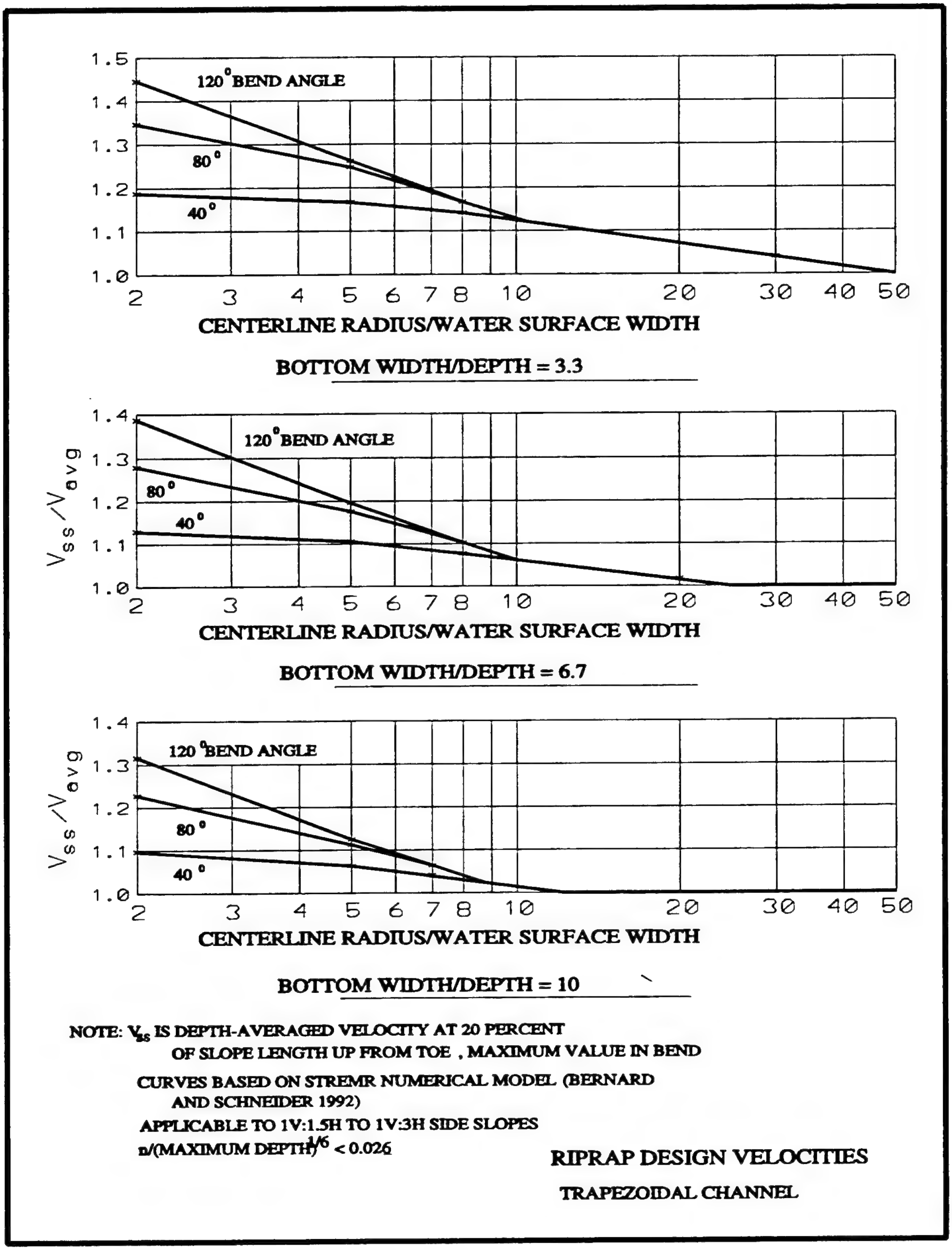


Figure 2. Velocity estimation for trapezoidal channels

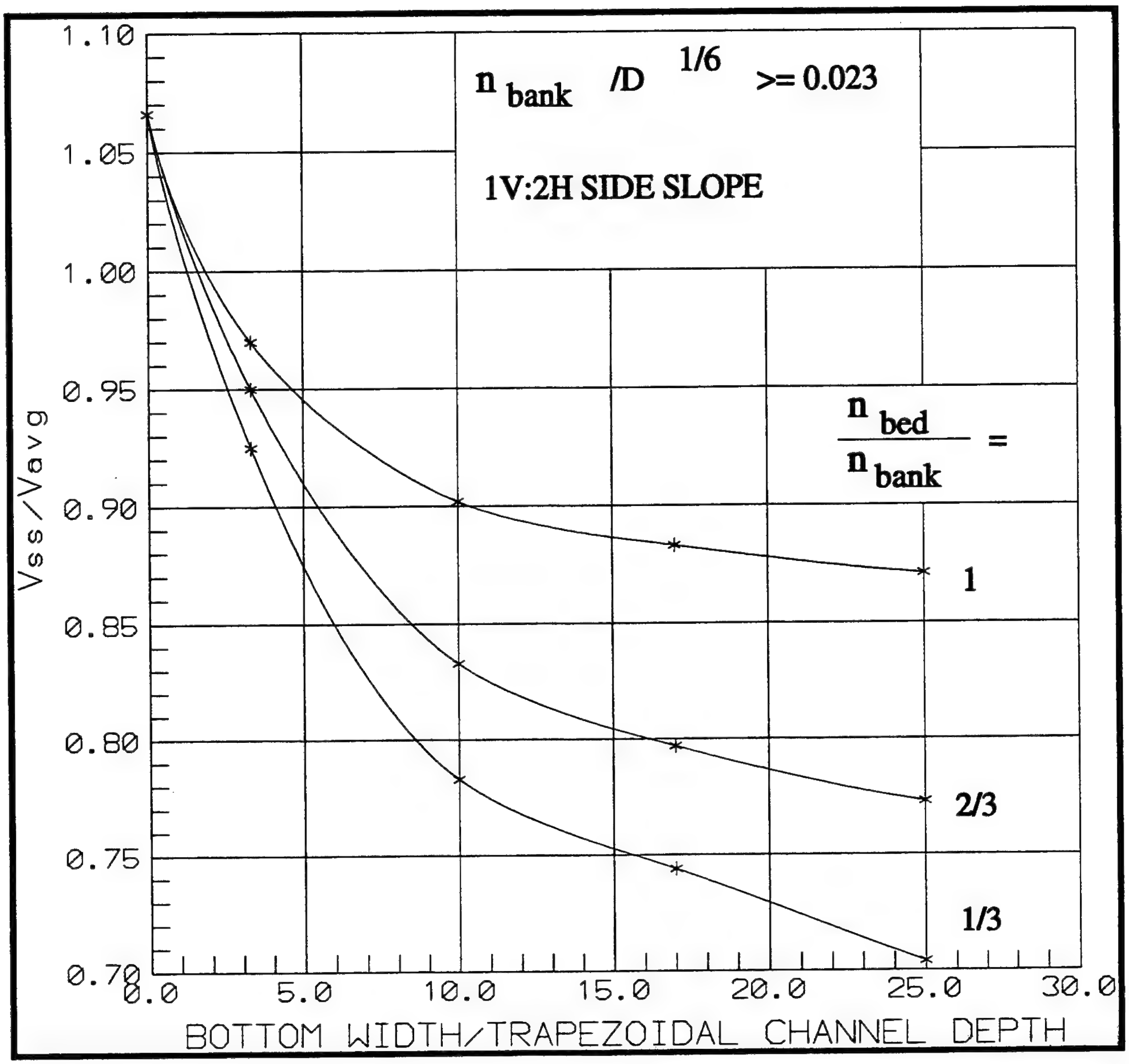
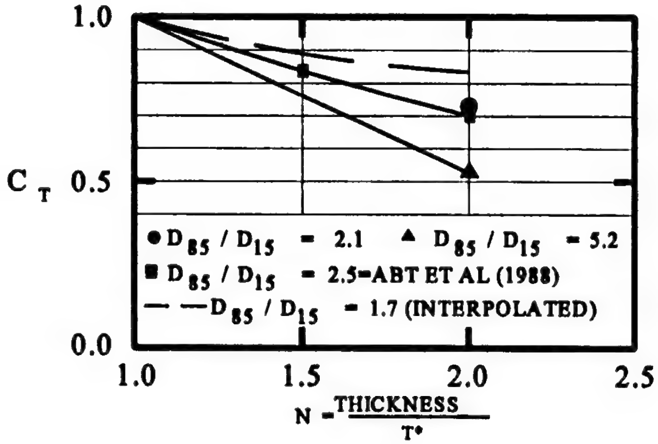


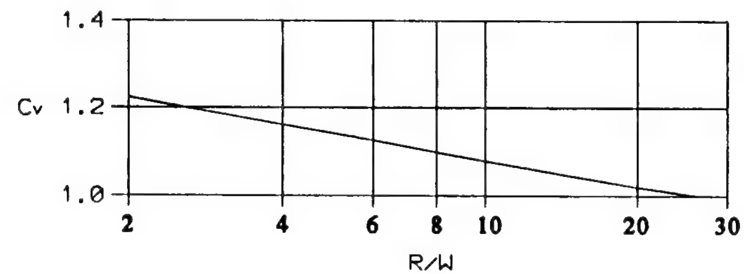
Figure 3. Side-slope velocities in long, straight channels having n_{bed}/n_{bank} = 1/3, 2/3, and 1



WHERE C_T = CORRECTION FOR THICKNESS

$$= \frac{D_{30} \text{ FOR THICKNESS OF } T^*}{D_{30} \text{ FOR THICKNESS OF } T^*}$$

$T^* = 1D_{100}$ OR $1.5D_{30}$, WHICHEVER IS GREATER



$D_{30} = C_V * (D_{30}$ FROM PLATE 37)

WHERE C_V = CORRECTION FOR VERTICAL VELOCITY DISTRIBUTION

CORRECTION FOR VERTICAL VELOCITY DISTRIBUTION IN BEND AND RIPRAP THICKNESS

Figure 4. Correction for vertical velocity distribution and riprap thickness

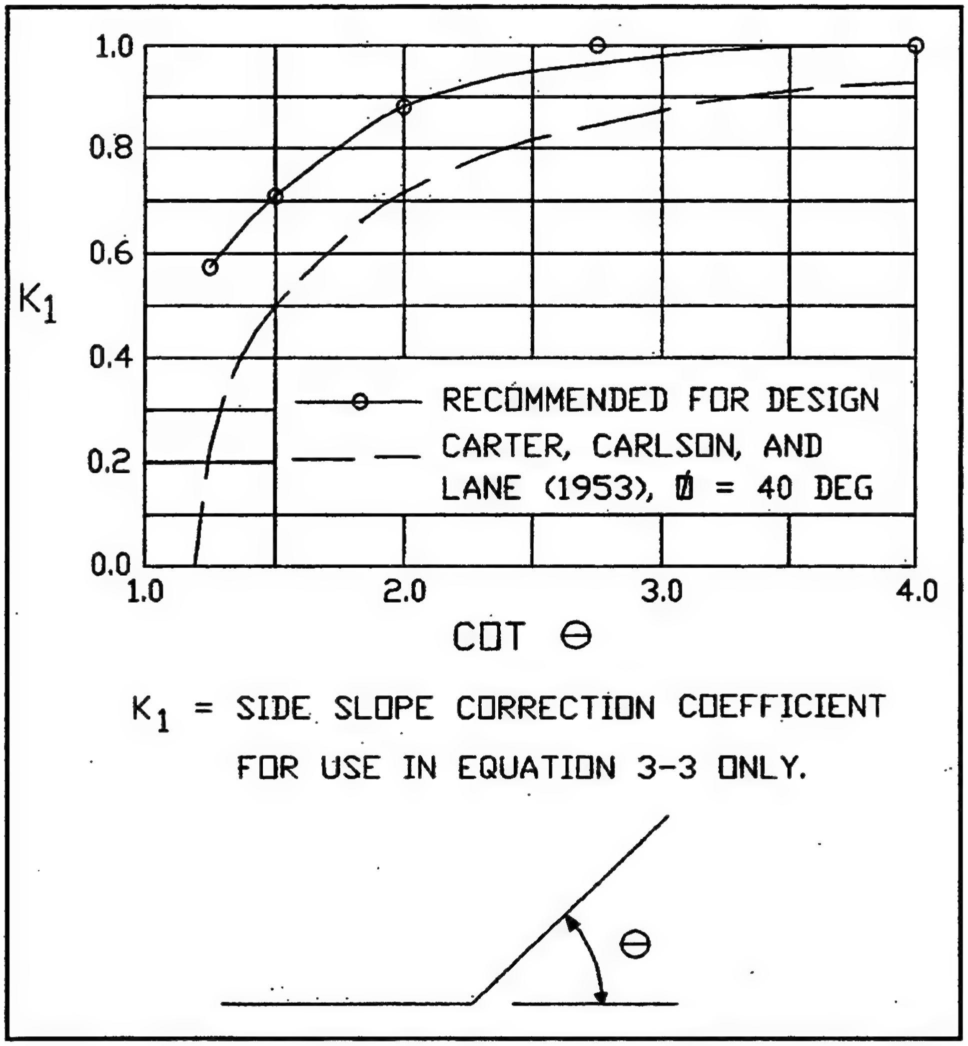


Figure 5. Correction for side slope angle

```
CHANLPRO INPUT FILE
FILE IS TEMP2IN DATE IS 10/02/1996 AT 0834 HRS

B  SB
L  VO
  10.00  VL
 600.00  BR
 200.00  WD
 165.00  UW
E  AL
  15.00  DP
   2.00  SS
   1.10  SF
```

Figure 6a. CHANLPRO input file for user inputs local depth average velocity, Channel Bend, ETL gradation, and side-slope riprap

```
CHANLPRO INPUT FILE
FILE IS TEMP1IN DATE IS 10/02/1996 AT 0828 HRS

B  SB
A  VO
N  CT
   8.00  VA
 600.00  BR
 200.00  WD
 165.00  UW
A  AL
  15.00  DP
   2.00  SS
   1.10  SF
```

Figure 6b. CHANLPRO input file for user inputs average channel velocity, natural channel, channel bend, alternate gradation, side-slope riprap

```
CHANLPRO INPUT FILE
FILE IS temp3in DATE IS 10/02/1996 AT 0847 HRS
S  SB
A  VO
T  CT
Y  W5
S  IS
     .00  BA
  100.00  BW
   15.00  FD
   10.00  VA
  165.00  UW
E  AL
   12.00  DP
    2.00  SS
    1.10  SF
```

Figure 6c. CHANLPRO input for user inputs average channel velocity, trapezoidal channel, straight channel > 5 channel widths downstream, ETL gradation

```
CHANLPRO INPUT FILE
FILE IS TEMP4IN DATE IS 10/02/1996 AT 0850 HRS
B  SB
A  VO
T  CT
I  IS
   80.00  BA
  100.00  BW
   15.00  FD
    8.00  VA
  600.00  BR
  160.00  WD
  165.00  UW
E  AL
   12.00  DP
    2.00  SS
    1.10  SF
```

Figure 6d. CHANLPRO input file for user inputs average channel velocity, trapezoidal channel, channel band, ETL gradation, and invert riprap

```
SB = Planform, S is straight reach, B is bend
UW = UNIT WEIGHT OF STONE, LB/FT³
DP = LOCAL FLOW DEPTH IN CHANNEL, FT
SS = CHANNEL SIDE SLOPE, COTAN OF ANGLE
BR = MINIMUM CENTERLINE BEND RADIUS, FT
WD = WATER SURFACE WIDTH AT UPSTREAM END OF BEND, FT
VO = VELOCITY OPTION, LOCAL (L) OR AVERAGE CHANNEL (A)
CT = CHANNEL TYPE, NATURAL (N) OR TRAPEZOIDAL (T)
VA = AVERAGE CHANNEL VELOCITY, FT/SEC
VL = LOCAL DEPTH AVERAGED VELOCITY, FT/SEC
IS = TRAPEZOIDAL CHANNEL RIPRAP, I FOR INVERT OR S FOR SIDE
     SLOPE
BA = BEND ANGLE IN TRAPEZOIDAL CHANNEL, DEG
BW = BOTTOM WIDTH IN TRAPEZOIDAL CHANNEL, FT
FD = MAXIMUM DEPTH IN TRAPEZOIDAL CHANNEL, FT
AL = ETL (E) OR ALTERNATE (A) GRADATION
W5 = Is straight reach > 5 channel widths downstream of anything
     causing a flow imbalance, Y or N
SF = SAFETY FACTOR, MINIMUM = 1.1
```

Figure 7. Two-letter designator used in input files in CHANLPRO

Name	D_{30}(min)	D_{100}(max)	D_{85}/D_{15}
GRADED#1	0.31	12.0	3.2
GRADED#2	0.43	16.0	3.0
GRADED#3	0.59	22.0	3.0
GRADED#4	0.79	28.0	2.8
GRADED#5	1.02	36.0	2.8

Figure 8. File "ALT.GRD"

```
FILE IS TEMP2OUT DATE IS 10/02/1996 AT 0834 HRS
INPUT FILE USED IS TEMP2IN


VO=L, ETL GRADATION, BEND



    PROGRAM OUTPUT FOR A CHANNEL WITH A KNOWN LOCAL
       DEPTH AVERAGED VELOCITY, BEND WAY
                  INPUT PARAMETERS
    SPECIFIC WEIGHT OF STONE,PCF                165.0
    MINIMUM CENTER LINE BEND RADIUS,FT          600.0
    WATER SURFACE WIDTH,FT                      200.0
    FLOW DEPTH,FT                                15.0
    CHANNEL SIDE SLOPE,1 VERT: 2.00 HORZ
    LOCAL DEPTH AVG VELOCITY,FPS                10.00
    SIDE SLOPE CORRECTION FACTOR K1               .88
    CORRECTION FOR VELOCITY PROFILE IN BEND      1.19
    RIPRAP DESIGN SAFETY FACTOR                  1.10


                          SELECTED STABLE GRADATIONS
                                ETL GRADATION

    NAME     COMPUTED D30(MIN)  D100(MAX)  D85/D15  N=THICKNESS/    CT  THICKNESS
              D30 FT    FT         IN                D100(MAX)             IN
     1                 .37        9.00       1.70    NOT STABLE
     2         .48     .48       12.00       1.70       1.35       .92    16.2
     3         .52     .61       15.00       1.70       1.00      1.00    15.0

  D100(MAX)        LIMITS OF STONE WEIGHT,LB          D30(MIN)  D90(MIN)
     IN           FOR PERCENT LIGHTER BY WEIGHT          FT        FT
                   100          50          15
   12.00      86     35     26     17     13     5      .48       .70
   15.00     169     67     50     34     25    11      .61       .88

          EQUIVALENT SPHERICAL DIAMETERS IN INCHES
  D100(MAX)  D100(MIN)  D50(MAX)  D50(MIN)  D15(MAX)  D15(MIN)
   12.0         8.8        8.0       7.0       6.3       4.8
   15.0        11.1       10.0       8.8       7.9       6.0
```

Figure 9. CHANLPRO output file for user inputs local depth averaged velocity, channel bend, ETL gradation, and side-slope riprap

```
FILE IS TEMP1OUT DATE IS 10/02/1996 AT 0828 HRS
INPUT FILE USED IS TEMP1IN


VO=A, CT=N, BEND, ALTERNATE GRADATION



    PROGRAM OUTPUT FOR A NATURAL CHANNEL SIDE SLOPE RIPRAP, BEND WAY
                   INPUT PARAMETERS
    SPECIFIC WEIGHT OF STONE,PCF                  165.0
    MINIMUM CENTER LINE BEND RADIUS,FT            600.0
    WATER SURFACE WIDTH,FT                        200.0
    FLOW DEPTH,FT                                  15.0
    CHANNEL SIDE SLOPE,1 VERT: 2.00 HORZ
    AVERAGE CHANNEL VELOCITY,FPS                   8.00
    COMPUTED LOCAL DEPTH AVG VEL,FPS              11.94
    (LOCAL VELOCITY)/(AVG CHANNEL VEL)             1.49
    SIDE SLOPE CORRECTION FACTOR K1                 .88
    CORRECTION FOR VELOCITY PROFILE IN BEND        1.19
    RIPRAP DESIGN SAFETY FACTOR                    1.10


                         SELECTED STABLE GRADATIONS
                            ALTERNATE GRADATION

    NAME     COMPUTED D30(MIN)  D100(MAX)  D85/D15  N=THICKNESS/  CT   THICKNESS
              D30 FT    FT         IN                 D100(MAX)           IN
  GRADED#3    .59       .59      22.00      3.00      1.80        .73    39.6
  GRADED#4    .79       .79      28.00      2.80      1.08        .97    30.1
  GRADED#5    .81      1.02      36.00      2.80      1.00       1.00    36.0
```

Figure 10. CHANLPRO output file for user inputs average channel velocity, natural channel, channel bend, alternate gradation, and side-slope riprap

```
FILE IS temp3out DATE IS 10/02/1996 AT 0847 HRS
INPUT FILE USED IS temp3in
VO=A, CT=T, STRAIGHT CHANNEL, >5 CHANNEL WIDTHS DOWNSTREAM,
ETL GRADATION

    PROGRAM OUTPUT FOR A TRAPEZOIDAL CHANNEL SIDE SLOPE, STRAIGHT REACH
STRAIGHT REACH IS > 5 WS WIDTHS DS OF ANYTHING CAUSING A FLOW IMBLANCE
                        INPUT PARAMETERS
    SPECIFIC WEIGHT OF STONE,PCF                    165.0
    FLOW DEPTH,FT                                    12.0
    CHANNEL SIDE SLOPE,1 VERT: 2.00 HORZ
    AVERAGE CHANNEL VELOCITY,FPS                    10.00
    COMPUTED LOCAL DEPTH AVG VEL,FPS                 9.28
    (LOCAL VELOCITY)/(AVG CHANNEL VEL)                .93
    BEND ANGLE,DEG TRAP SECT                          .00
    BOTTOM WIDTH,FT TRAP SECT                      100.00
    FLOW DEPTH,FT TRAP SECT                         15.00
    SIDE SLOPE CORRECTION FACTOR K1                   .88
    CORRECTION FOR VELOCITY PROFILE IN BEND          1.00
    RIPRAP DESIGN SAFETY FACTOR                      1.10


                        SELECTED STABLE GRADATIONS
                              ETL GRADATION

    NAME    COMPUTED D30(MIN)  D100(MAX)  D85/D15  N=THICKNESS/   CT  THICKNESS
             D30 FT    FT        IN                  D100(MAX)            IN
     1        .37      .37      9.00       1.70        1.15        .96   10.4
     2        .38      .48     12.00       1.70        1.00       1.00   12.0

  D100(MAX)         LIMITS OF STONE WEIGHT,LB           D30(MIN)  D90(MIN)
     IN           FOR PERCENT LIGHTER BY WEIGHT             FT        FT
                   100          50           15
    9.00      36      15      11       7       5      2    .37       .53
   12.00      86      35      26      17      13      5    .48       .70

            EQUIVALENT SPHERICAL DIAMETERS IN INCHES
  D100(MAX)  D100(MIN)   D50(MAX)   D50(MIN)   D15(MAX)   D15(MIN)
    9.0        6.6         6.0        5.3        4.8        3.6
   12.0        8.8         8.0        7.0        6.3        4.8
```

Figure 11. CHANLPRO output file for user inputs average channel velocity, trapezoidal channel, straight channel > 5 channel widths downstream, ETL gradation, and side-slope riprap

```
FILE IS TEMP4OUT DATE IS 10/02/1996 AT 0850 HRS
INPUT FILE USED IS TEMP4IN

VO=A, CT=T, BEND, ETL GRADATION, INVERT RIPRAP

    PROGRAM OUTPUT FOR A TRAPEZOIDAL CHANNEL INVERT, BEND WAY
                   INPUT PARAMETERS
    SPECIFIC WEIGHT OF STONE,PCF                    165.0
    MINIMUM CENTER LINE BEND RADIUS,FT              600.0
    WATER SURFACE WIDTH,FT                          160.0
    FLOW DEPTH,FT                                    12.0
    CHANNEL SIDE SLOPE,1 VERT: 2.00 HORZ
    AVERAGE CHANNEL VELOCITY,FPS                     8.00
    COMPUTED LOCAL DEPTH AVG VEL,FPS                 9.68
    (LOCAL VELOCITY)/(AVG CHANNEL VEL)               1.21
    BEND ANGLE,DEG TRAP SECT                        80.00
    BOTTOM WIDTH,FT TRAP SECT                      100.00
    FLOW DEPTH,FT TRAP SECT                         15.00
    SIDE SLOPE CORRECTION FACTOR K1                   .88
    CORRECTION FOR VELOCITY PROFILE IN BEND          1.17
    RIPRAP DESIGN SAFETY FACTOR                      1.10

                         SELECTED STABLE GRADATIONS
                              ETL GRADATION

    NAME     COMPUTED D30(MIN)  D100(MAX)  D85/D15  N=THICKNESS/   CT  THICKNESS
              D30 FT     FT        IN                 D100(MAX)          IN
     1                  .37       9.00      1.70     NOT STABLE
     2         .48      .48      12.00      1.70        1.16      .96   13.9
     3         .50      .61      15.00      1.70        1.00     1.00   15.0

  D100(MAX)       LIMITS OF STONE WEIGHT,LB         D30(MIN)  D90(MIN)
     IN         FOR PERCENT LIGHTER BY WEIGHT          FT        FT
                  100          50          15
   12.00       86     35    26     17     13     5     .48       .70
   15.00      169     67    50     34     25    11     .61       .88

           EQUIVALENT SPHERICAL DIAMETERS IN INCHES
  D100(MAX)  D100(MIN)  D50(MAX)  D50(MIN)  D15(MAX)  D15(MIN)
   12.0        8.8        8.0       7.0       6.3       4.8
   15.0       11.1       10.0       8.8       7.9       6.0
```

Figure 12. CHANLPRO output file for user inputs average channel velocity, trapezoidal channel, channel bend, ETL gradation, and invert riprap

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13. ABSTRACT *(Maximum 200 words)*

This document provides a user's manual for Windows program CHANLPRO, which replaces RIPRAP15 and addresses the following three areas pertinent to the design of channel protection:

a. U.S. Army Corps of Engineers riprap design guidance for placement in the dry for channels subjected to velocity forces in low turbulent flow based on USACE guidance.
b. Guidance for the design of gabion mattresses for the same flow conditions as the riprap design guidance.
c. guidance for estimating scour depth in erodible channels

Data used to develop the methods used herein for riprap and gabion mattresses were limited to channel slopes less than or equal to 2 percent. Program developers came to recognize that the most uncertain of riprap design is the determination of imposed force, which can be found using the depth-averaged velocity at the point of interest. For this reason, many of the changes that were incorporated into the CHANLPRO program are directed at helping the designer determine the local depth-averaged velocity.

14. SUBJECT TERMS

CHANLPRO	Riprap design
Channel protection	Scour depth
Gabion mattresses	

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